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Microgravity Heat Transfer Mechanisms in the Nucleate Pool Boiling and Critical Heat Flux Regimes Using a Novel Array of Microscale Heaters

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INTRODUCTION

Boiling as a heat transfer mechanism is becoming of increasing importance to space based hardware due to increases in the amounts of heat that must be removed with little increase in temperature. An understanding of microgravity effects on boiling mechanisms is therefore critical to the proper design of heat removal equipment for use in space-based applications. Experiments to date have shown that stable, subcooled boiling on flat plates in microgravity environments is possible, although usually with reductions in heat transfer coefficients of between 10% to 50%. It is presently thought that coalescence and condensation of bubbles away from the heater cause oscillatory motions within the surrounding liquid, thereby providing a continual supply of liquid from the bulk of the pool to the base of the bubble just above the heater. Almost all research pertaining to boiling in microgravity environments, however, has thus far been either of a qualitative nature (photographic studies) with some average wall heat flux/wall temperature measurements, analytical work, or numerical simulations. In the studies where the heat transfer coefficients were measured, the heated surface was always comparable to or much larger than the bubble sizes, so only average heat transfer rates over the entire heated surface were obtained. Very little experimental data is available regarding the *local* heat transfer rates under and around the bubbles as they grow and depart from the surface. Such information, especially when correlated with visual studies, can provide much needed information regarding the relevant wall heat transfer mechanisms during the bubble departure cycle by pinpointing when and where in the cycle large amounts of heat are removed. Microgravity effects on critical heat flux levels (the maximum heat flux level that can be attained without a catastrophic increase in heater temperature) is another very important area that must be addressed if boiling is to be used reliably as a heat removal mechanism. Although critical heat flux is known to decrease with decreasing gravity, very little quantitative information is available due to the use of constant wall heat flux heaters (as opposed to constant wall temperature heaters).

There are two primary objectives to this study: 1) to determine the relative contributions of various heat transfer mechanisms to the overall heat flux in subcooled, nucleate pool boiling of a fluorinert on a flat plate in terrestrial gravity, and 2) to obtain quantitative data regarding local heat transfer levels at critical heat flux in terrestrial gravity. (A proposal to obtain the same data under microgravity environments has recently been submitted). To accomplish these objectives, a novel heater surface consisting of a two-dimensional array of microscale heaters is used to measure the heat transfer from a surface at many points underneath a bubble in conjunction with visual studies. Each individual heater is much smaller than a single bubble, although the heater array is of the same order or larger than a single bubble. Each heater represents one resistance in a bridge, and is be kept at constant temperature by an electronic feedback loop. By measuring the voltage required to keep each individual heater at a constant temperature, two dimensional maps of the power and the heat transfer coefficient from the heater surface to the bulk liquid can be obtained. This heater array enables the heat transfer to a surface during the bubble growth and departure process to be measured with very high temporal and spatial resolution. Furthermore, data can be obtained in the critical heat flux and transition boiling regions without the danger of heater burnout because the heaters are operated in the constant temperature mode.

SUMMARY OF WORK PERFORMED

Construction of an experimental apparatus to perform the above measurements in earth gravity was initiated in May, 1994 under NASA sponsorship. The prototype heater construction has been completed, along with the design and construction of the feedback control circuit, and the computer control circuitry for controlling the resistance of the heaters. The data acquisition system also has been acquired. Each of these accomplishments is discussed below.

Description of heater array. The heater array is constructed on a highly doped silicon wafer using VLSI techniques. A schematic of the wafer construction is shown on Figure 1. The Si wafer serves as the substrate and

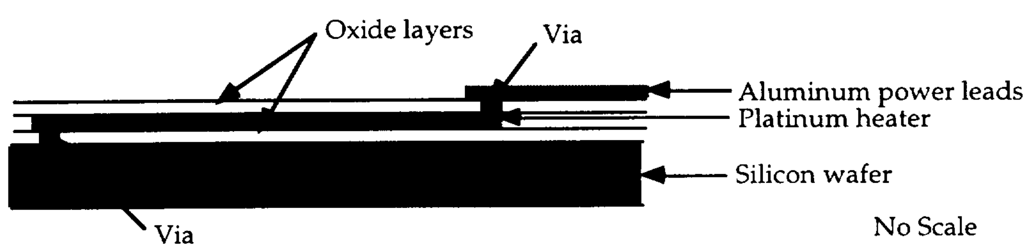

Figure 1--Schematic of heater construction.

electrically grounds one side of the heaters. A layer of SiO_2 is first grown on the wafer so that the heaters can be electrically insulated. Vias cut into this layer allow electrical connections from the heaters to the wafer. The vias are filled with metal, and an array of platinum resistance heaters in a serpentine pattern is then deposited onto the SiO_2. Another layer of SiO_2 is deposited on top of the platinum resistance heaters as insulation. Vias cut into the top SiO_2 layer allow connections between the power leads and the heaters. The vias are filled with metal and the aluminum power leads are deposited. Below the Si wafer is a guard heater at the same temperature as the heaters, thereby eliminating heat conduction within the substrate, so all power flowing into the heaters is transferred to the fluid. A photo of a single heater is shown on Figure 2. The prototype heater array has 148 of these heaters

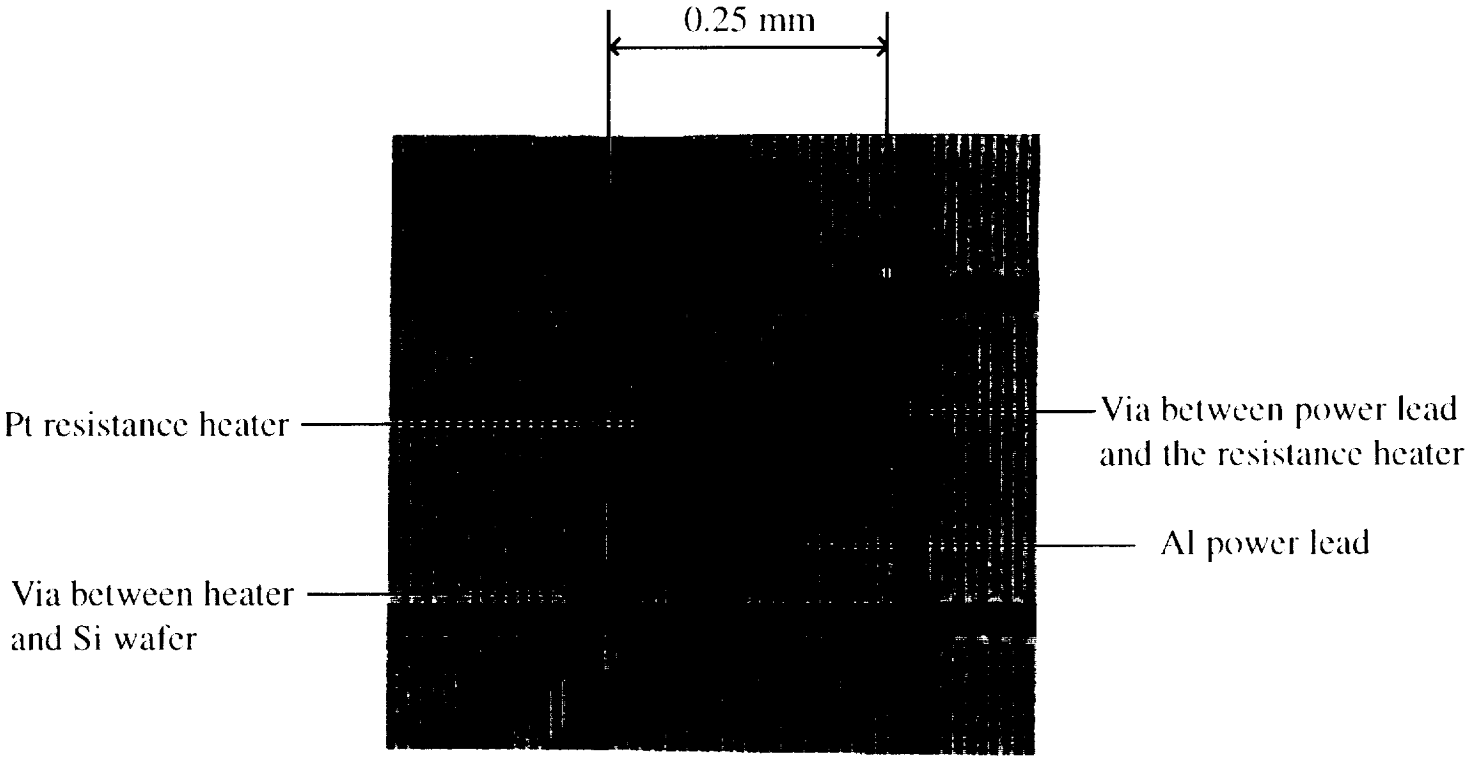

Figure 2--Photograph of a single heater in the array.

within a 3 mm diameter circle. The resistance heater, the power leads, and the vias are all clearly visible. Each heater has an overall size of 0.25 mm x 0.25 mm. Although the size of the heaters precludes measurement of the local heat transfer during bubble initiation (which occurs on μm length scales), wall heat transfer during bubble growth and departure can be measured easily. The heater lines are 5 μm wide and about 6000 μm in total length, with spacing between heater lines of 5 μm. Very little error is introduced by having spaces between the heater lines. A numerical calculation of the steady state temperature distribution within the prototype heater array was performed using the commercially available CFD code FLUENT assuming a heat transfer coefficient of 30,000 W/m^2-K and a constant heater to freestream temperature difference of 10 °C. The results are shown on Figure 3. The maximum temperature depression at the surface is seen to be only 0.2 °C between the heater lines, so the overall energy transferred from the wall to the fluid is very close to that which would be obtained for the ideal case of no space between the heater lines. An order of magnitude analysis showed that the diffusion of heat from the heater lines to the substrate material between the heaters occurs on time scales much smaller than those expected in the boiling process (10^{-8} s vs. 10^{-3} s, respectively). Although the uncertainty associated with the spacing between heater lines is small, a smaller spacing would be desirable. It is felt that the spacing between the heater lines can be decreased to 2 μm without much problem for the next generation heater array. The spacing between individual heaters will also be reduced.

About nine heater arrays can be made on a single wafer. The wafer is diced and a chip containing a single heater array is silver epoxied to a pin grid array (PGA). Connections between the PGA and the power leads are made by wire bonding. The PGA is then mounted onto a double-sided printed circuit board (PCB) which routes the connections to card edge connectors. A picture of the assembled components is shown in Figure 4.

Description of feedback circuit. A schematic of a feedback control circuit used to keep a heater at a constant temperature (constant resistance) is shown in Figure 5. The circuit is similar to the feedback loops used for constant temperature hot-wire anemometers. Each circuit provides a driver voltage to its respective heater and an output voltage that corresponds to the power being dissipated by the heating element. Along with the output voltages, each control circuit uses an input signal to select the desired temperature of the heating element. Because the heater is so thin (~2.0 μm), the frequency response of the heaters (10^6-10^7 Hz) is much higher than the bubble departure frequency (10^2-10^3 Hz). No frequency compensation circuitry is therefore needed. The resistance of the heater is controlled using a voltage controlled resistance (VCR). A VCR was chosen instead of a manual potentiometer so the heaters resistance could be computer controlled. This circuit was tested on a tungsten wire, a thermistor, and a thin layer of SnO_2

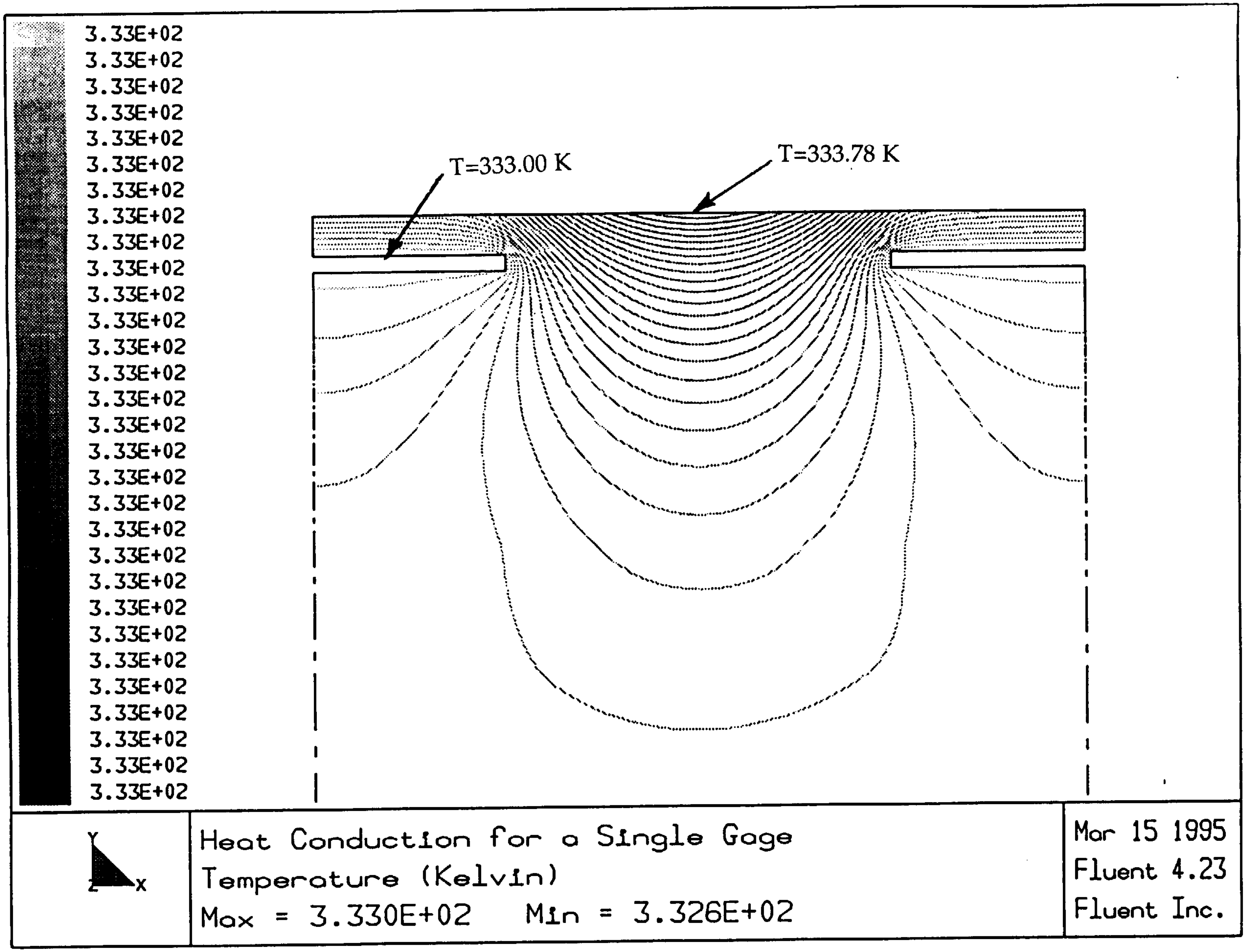

Figure 3--Fluent calculation of temperatures between heater lines.

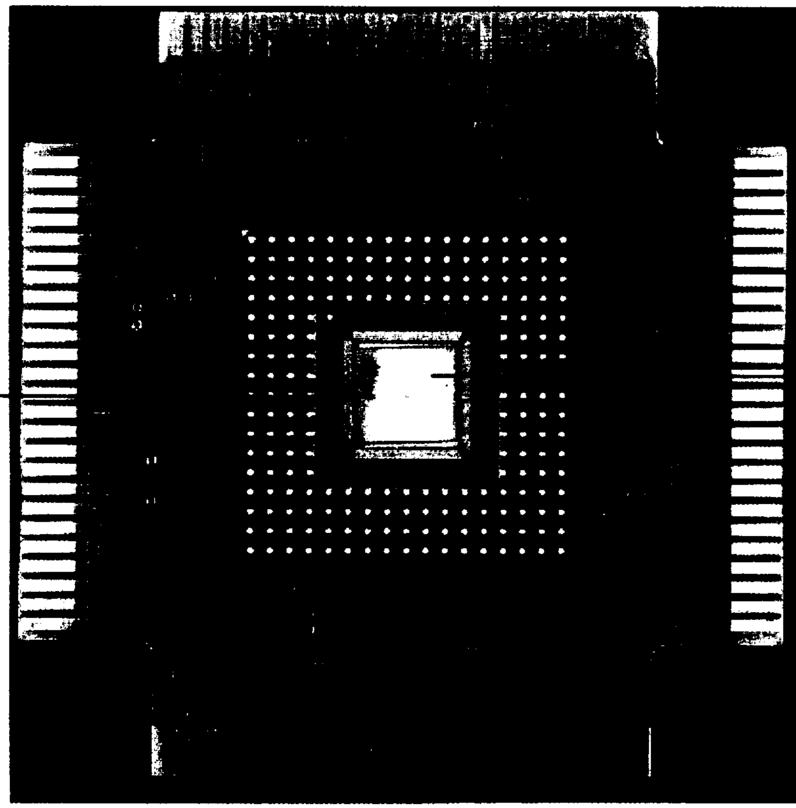

Figure 4--Photograph of a). the chip containing the heater array, b). the Pin Grid Array (PGA), and c). the Printed Circuit Board (PCB).

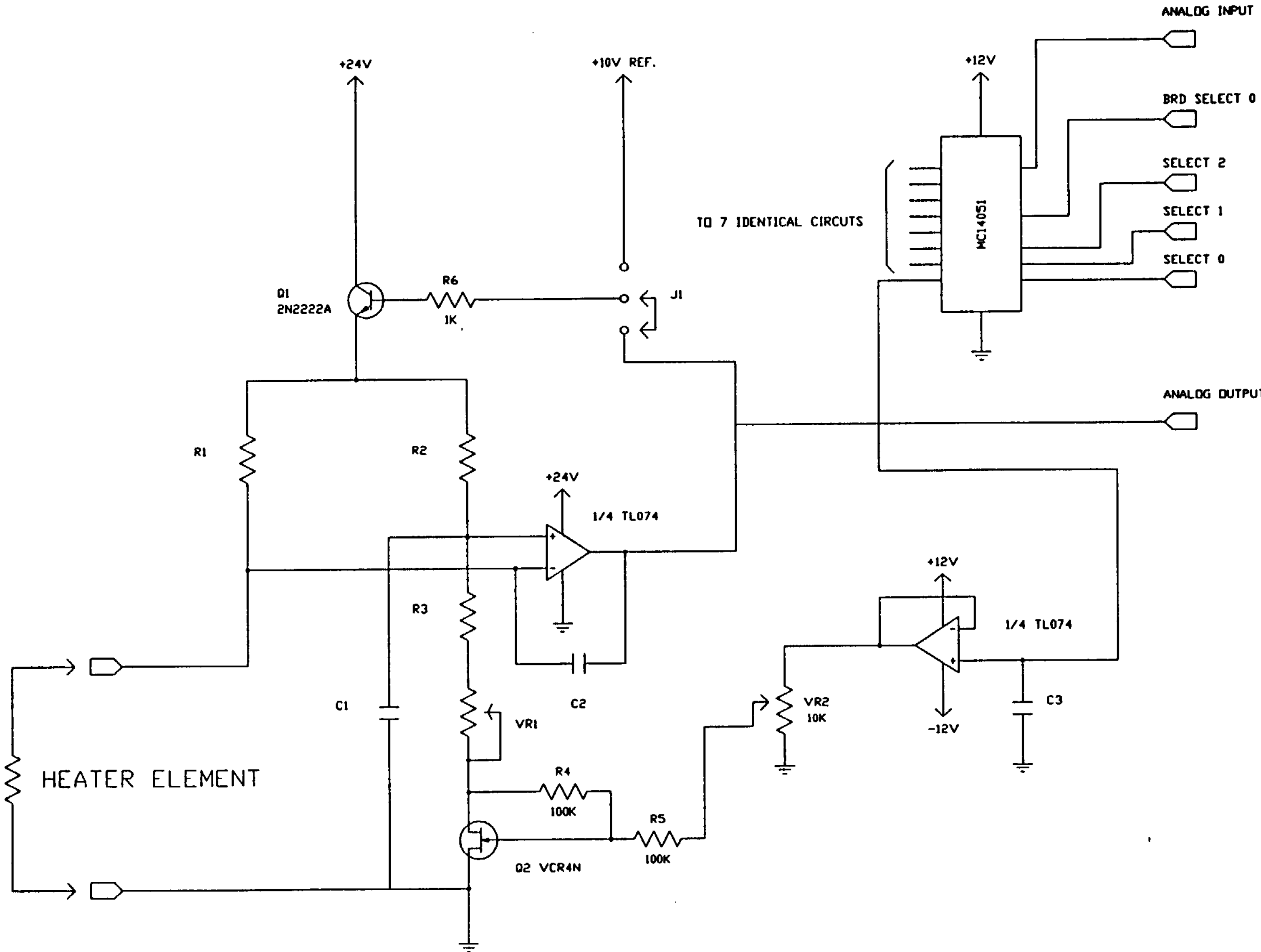

Figure 5--Schematic of feedback control circuits for heater control.

deposited on a glass substrate. The thermistor and tungsten wire were able to detect slight breezes blowing in through an open window, and the thermistor was able to boil water. The SnO_2 heater is most similar to the actual heater configuration because it consists of a conducting film deposited on an insulating substrate. The heater area was 1 mm x 2.5 mm, with a resistance of 1500 W, and was immersed in a bath of acetone at saturation. At high enough heater temperatures, boiling took place on the SnO_2 surface. Natural convection, forced convection, and boiling were all easily detected by the circuit. One could easily see that departure of bubbles from the heater surface corresponded to increases in circuit output. Testing of a circuit using the actual heaters is currently underway.

The frequency response of the circuit was measured to be in excess of 20,000 Hz by removing the heater, inputting a square wave, and measuring the circuit output; this is much faster than the frequencies expected during the bubble growth and departure cycle. The circuit has been laid out on a PCB, with each board containing 16 circuits. The layout of the control circuits on the PCB is shown in Figure 6. Ten of these PCB's will be fabricated and housed in an enclosure.

Description of computer control circuit. A schematic of the circuit used to set the temperatures of the individual heaters in the array using computer control is shown on Figure 7. The computer controls the temperature of each heating element, measures the power used by each heating element using a data acquisition system, and stores this information in a file on the hard disk until an interrupt is received. Because data collection must occur very quickly, the data collection is handled by the main computer and a data acquisition unit, and control of the heaters is delegated to a separate microcontroller. The use of a separate system for heater control maximizes the data acquisition capabilities of the main computer since it will not need to share processing time for the heater control process. The microcontroller communicates with the main computer through a standard RS-232 serial data port at 9600 baud. During the experiment, a data table is downloaded to the microcontroller at the beginning of each data acquisition session. The data table includes control information for each heater element at ten different temperatures. At the beginning of each data acquisition session, the main computer outputs a string of control characters to the microcontroller to select one of the ten different temperatures, then is completely dedicated to the data acquisition process. If another set of ten temperatures is desired, the main computer will be required to stop the data acquisition process and download a new data table to the microcontroller. The above circuit has been constructed and tested on a protoboard. It is presently being laid out on a PCB.

Description of data acquisition system (DAS). The DAS consists of low-pass filters at the output of each bridge, a high speed multiplexer, and a 16 bit A/D converter sampled by a personal computer. Separate channels are used to measure the time, and the bulk liquid temperature and pressure. The Daqbook 216 from IO Tech was chosen due to its low cost, high resolution (16 bits), high data acquisition rate (100 kHz), portability, and expandability (256

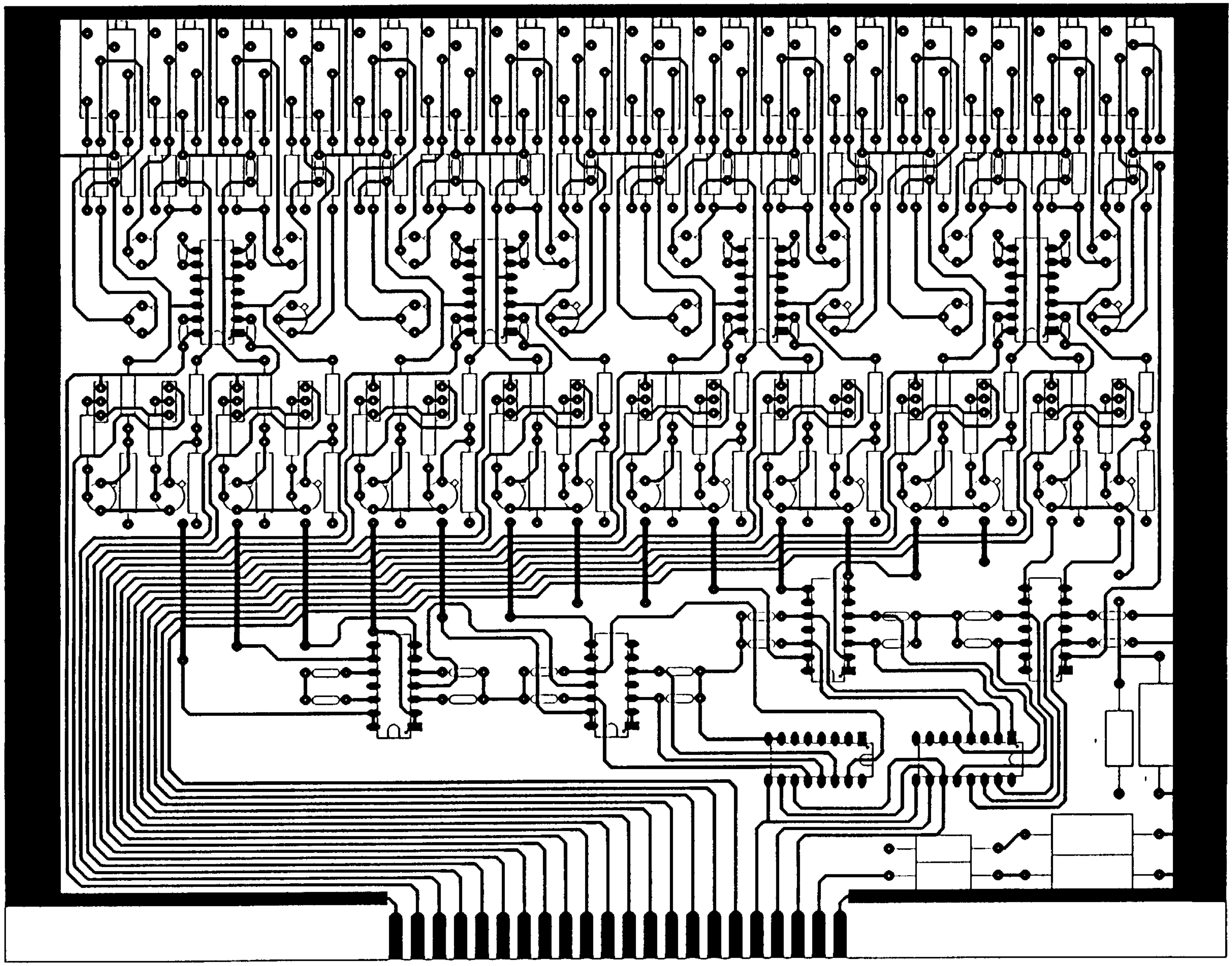

Figure 6--Layout of 16 control circuits on a PCB board showing the components, and the top and bottom traces.

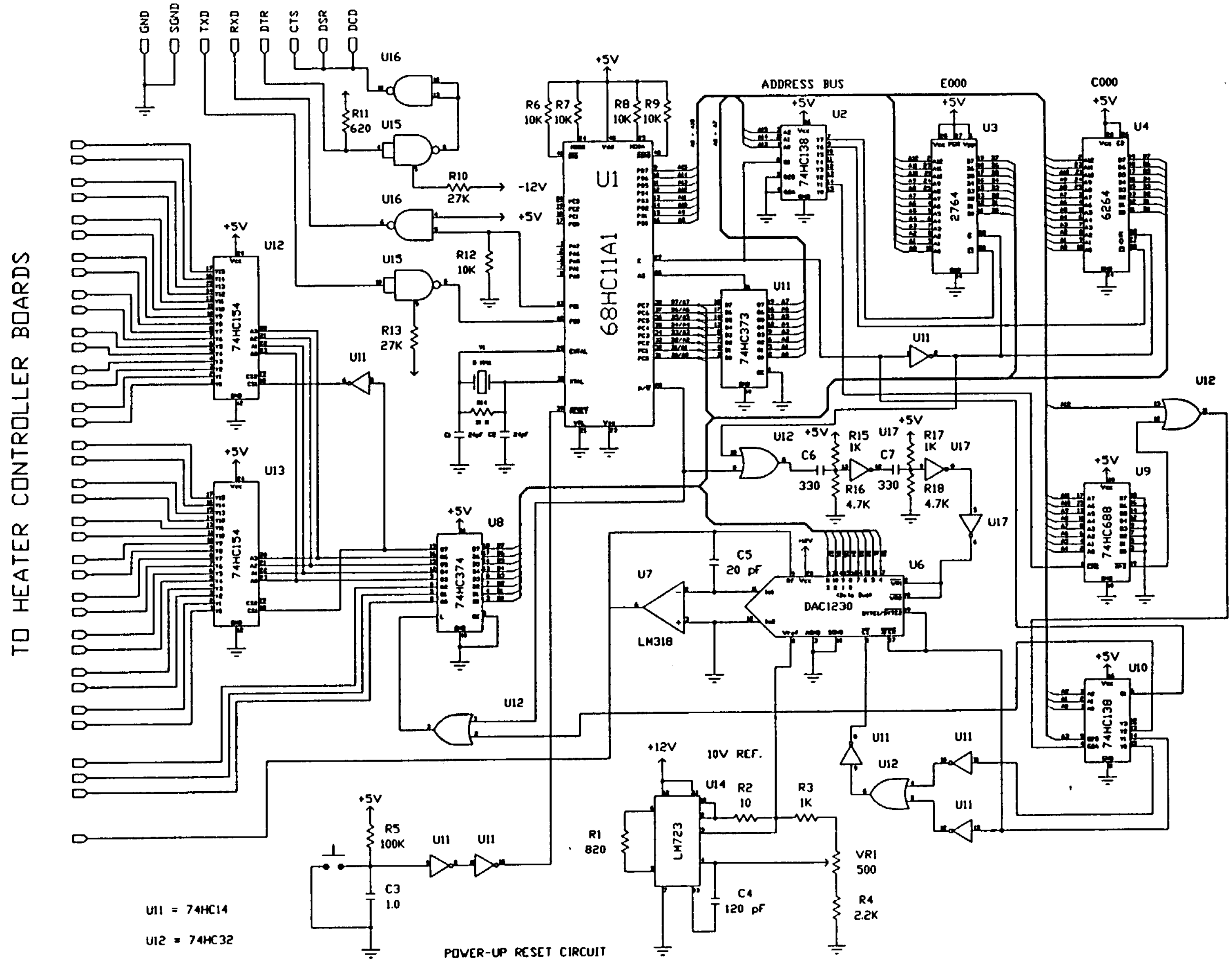

Figure 7--Computer control circuit.

channels maximum). Direct connection to a personal computer is performed through a PCMCIA port.

WORK TO BE COMPLETED DURING THE FOLLOWING YEAR

During the remaining portion of the contract, which expires 5/96, the following work is to be completed. The control circuits will be built, the heaters will be calibrated, and data reduction and visualization software will be written. A test vessel to house the heater array that enables data to be taken at saturation and subcooled conditions will be built. A schematic of this test vessel is shown in Figure 8. Boiling curves and contours of the wall heat transfer coefficient vs. time underneath single bubbles as they grow and depart from the surface will be obtained for saturated and subcooled conditions in earth gravity for nucleate boiling and critical heat flux. Papers describing the heater array and the data acquisition hardware, and the results of the study will be submitted to an appropriate Journal.

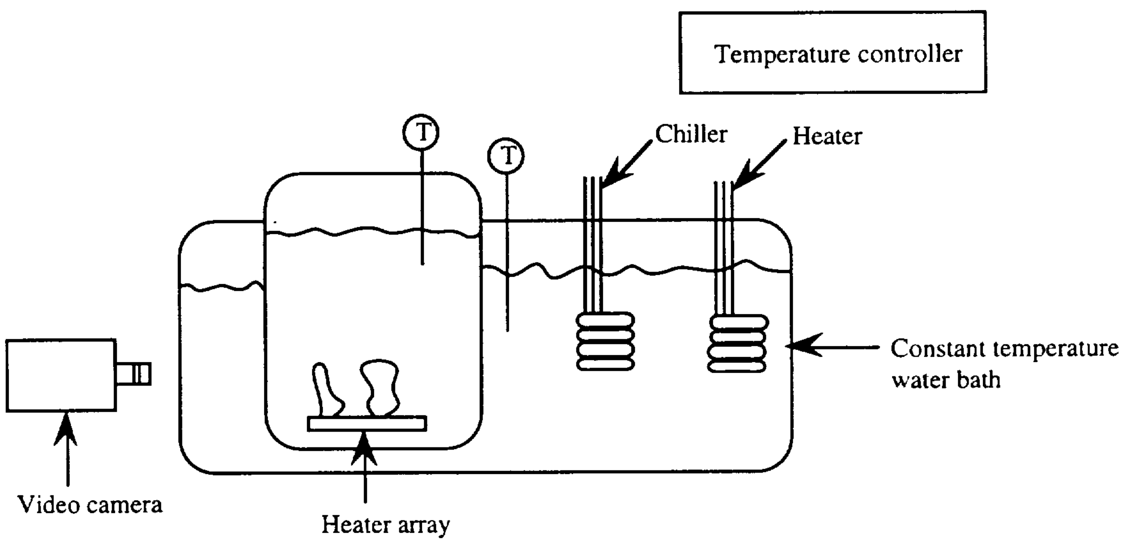

Figure 8--Schematic of test facility.